CONSTRUCTION CYCLE 6 (CC-6) REVISITED

FATIGUE ANALYSIS
AND
ECONOMIC AND DESIGN IMPLICATIONS

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ABSTRACT

For some time, industry has indicated that concrete with high flexural strength will cause embrittlement of concrete pavements and premature cracking, and as such, flexural strengths were limited for rigid pavement thickness design. As a result, and based on only anecdotal information, Federal Aviation Administration (FAA) Advisory Circular 150/5320-6E [1], states that the thickness of rigid airport pavements should be computed based on a 90-day concrete flexural strength ranging between 600 psi and 700 psi, independent of the flexural strength of the concrete mix determined according to the guidelines of FAA Advisory Circular 150/5370-10 [2], which requires a 28-day flexural strength for acceptance. FAA Advisory Circular 150/5320-6E also states that the 28-day strength for specification development should be approximately 5% less than the 90-day strength, resulting in a specified range in 28-day flexural strengths of 570 psi to 665 psi. In many areas of the country, 28-day and 90-day flexural strengths are commonly much higher than 700 psi when produced with relatively low cement contents and utilizing mix design optimization techniques. Also, many engineers believed that, based on anecdotal information, the performance of rigid pavements was improved when asphalt, in lieu of cement, treated subbase was used.

Construction Cycle 6 (CC-6) at the National Airport Pavement Test Facility (NAPTF) was designed to test the technical validity of limiting the flexural strength requirements for thickness design to improve performance, as well as the relative performance of rigid pavements constructed on cement and asphalt stabilized subbases. The test items in CC-6 were constructed at uniform 12-inch thicknesses with three different concrete flexural strengths (nominally 500, 750, and 1,000 psi) on two different subbases (lean concrete and asphalt stabilized). Traffic testing, as reported in Brill [3] and Brill and Hao [4], demonstrated that the flexural strength of the test items was a good predictor of the life of the test items under full-scale traffic testing, suggesting that the 90-day, and consequently 28-day, flexural strength limitation can be raised. The pavements on the asphalt and cement stabilized subbase were also shown to provide comparative performance. These findings suggest the possibility of significant cost savings in pavement construction.

As part of CC-6, laboratory fatigue testing of beams from the test items was also performed. When normalized to the flexural strength, the results from the fatigue tests indicated that the characteristics of the laboratory determined fatigue life of the test item mixes were not significantly affected by the flexural strength of the mixes; however a statistical analysis of the laboratory fatigue test results was not performed.

The paper reviews the major findings from CC-6; statistically analyzes whether the normalized laboratory fatigue characteristics of concrete vary with flexural strength; and demonstrates the relative economic impact of implementing the major findings from CC-6.

BACKGROUND

The primary objectives of CC-6 [3] included:

- Investigate the relative effect of concrete flexural strength on performance; and
- Investigate the effect of cement stabilized vs. asphalt stabilized subbase on performance.

Planning for CC-6 began in 2009 with the geometric design for full scale test items, followed by selection of aggregates and sands for concrete mix designs. The laboratory mix designs were performed in early 2010 to provide three concrete mixes having nominal flexural strengths of 500 psi, 750 psi, and 1,000 psi, representing low, medium, and high strength concrete. This was believed to provide a sufficient spread in strengths to investigate the effect of flexural strength on performance during subsequent full strength and laboratory fatigue testing. The geometric layout for full scale testing is depicted in Figure 1, Brill [3].

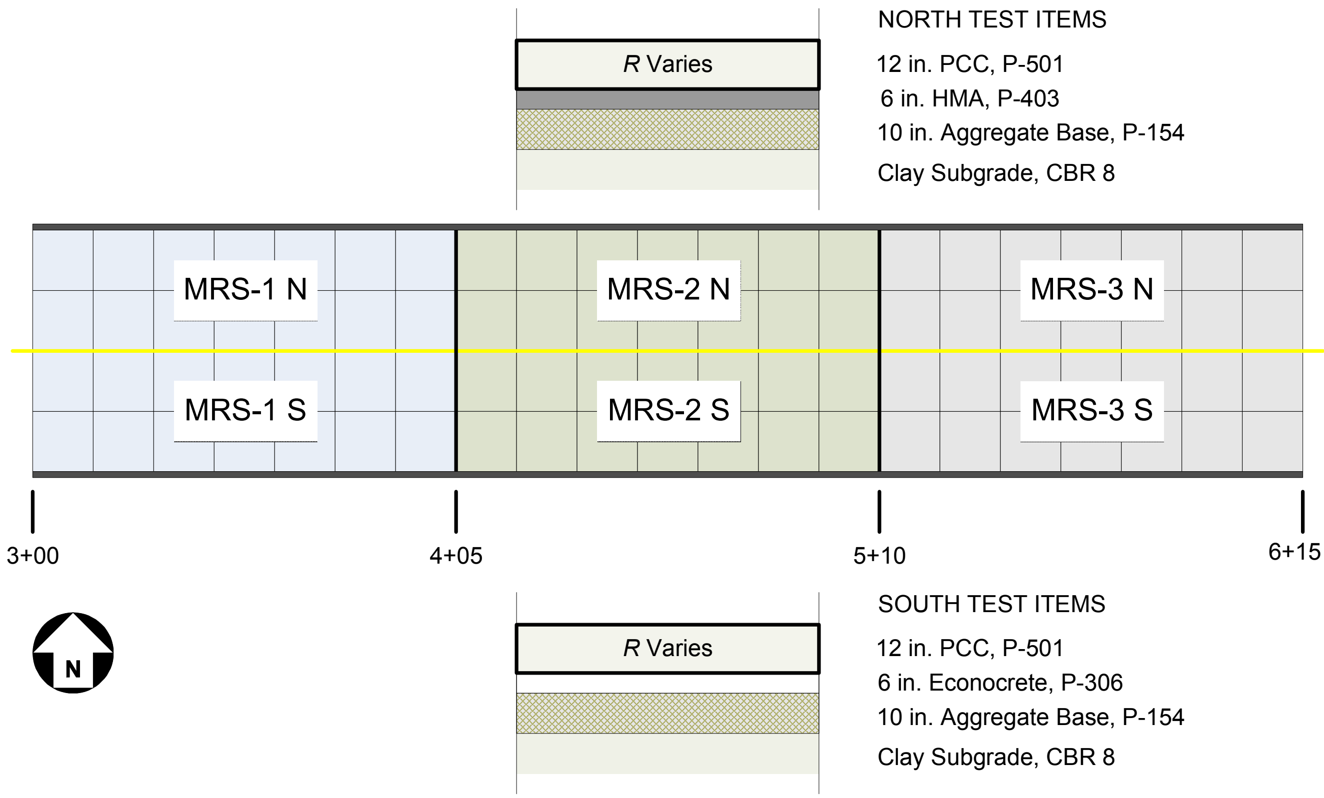

Figure 1. Layout of CC-6 Test Items.

An imported gravel aggregate was used for the 500 psi mix at a cement content of 460 lbs./cy and local crushed aggregate was used for the 750 psi and 1,000 psi mixes at cement contents of 500 lbs./cy and 680 psi/cy, respectively. Actual average flexural strengths for the low, medium, and high strength test items were 662 psi, 763 psi, and 1,007 psi, respectively.

Full scale trafficking was conducted during 2011 at a mixture of full scale wheel loads to promote early failure. A load compensation procedure reported in Brill [3] was used to compute equivalent passes to terminal condition, or “failure”, at 45,000 lbs. and 70,000 lbs. wheel loads, with terminal condition defined as Structural Condition Index (SCI) at or near zero. The equivalent load repetitions to failure for each test item and subbase are presented in Table 1.

The equivalent passes shown in Table 1 for the three concrete mixes indicate that concrete pavement life is strongly correlated to flexural strength, even at cement contents up to 680 lbs./cy, which is in the normal range for airport quality concrete pavement.

Further, there was no significant difference in the Structural Condition Index (SCI) between cement stabilized and asphalt stabilized subbases.

Table 1.
Equivalent Passes to Failure, Brill [3].

Test Item	Equivalent Passes @ 45 kips	Equivalent Passes @ 70 kips
MRS-1 North	9,108	63
MRS-1 South	7,834	54
MRS-2 North	577,393	1,855
MRS-2 South	572,096	1,838
MRS-3 North	9,909,051	4,696
MRS-3 South	11,175,129	5,296

Finally, based on free-free resonance tests, no correlations were found between flexural strength and elastic modulus. Both the 750 psi and 1,000 psi mixes had approximately the same elastic moduli of 6,500,000 psi and 6,600,000 psi, respectively, suggesting that the elastic modulus of concrete is more a function of aggregate type than flexural strength.

LABORATORY FATIGUE TESTING OF BEAM SAMPLES

Fatigue tests were performed at the FAA's NextGen Pavement Materials Laboratory on beams cast at the time of construction and beams cut from the concrete slabs after trafficking was completed. Publicly available details of the fatigue testing and beam sample acquisition are given in Brill [3] and Brill and Hao [4]. The beams cast from the MRS2 and MRS3 mixes during construction were spoiled during storage and fatigue results for those beams are not included here. A summary of the beams tested is given in Table 2. Figures 2 through 5 show the fatigue results after normalizing the fatigue strength for each test sample with respect to the flexural strength, expressed as a stress ratio (percent flexural strength). Linear regression equations and correlation coefficients are given for stress ratio versus Log_{10}(cycles to failure).

Table 2.
Summary of Flexural Strength and Number of Beams Tested in Fatigue.

Test Item	Target Strength[3, 4], psi	28-Day Strength[3,4], psi	Strength of Field-Cut Samples[4], psi	Number of Cast Beams	Number of Cut Beams
MRS1	500	662	660	39	16
MRS2	750	763	749	0	18
MRS3	1000	1007	932	0	19

Notes:
Strength is flexural strength measured according to ASTM C78.

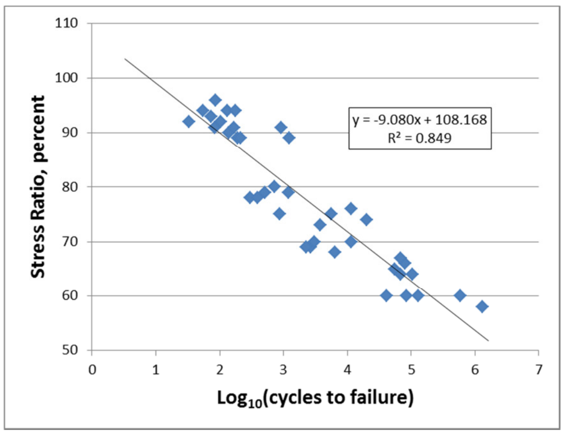

Figure 2. Fatigue Test Results for MRS1 Cast Beams.

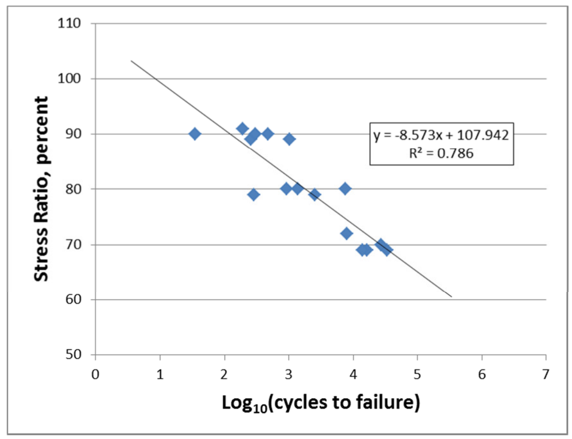

Figure 3. Fatigue Test Results for MRS1 Field-Cut Beams.

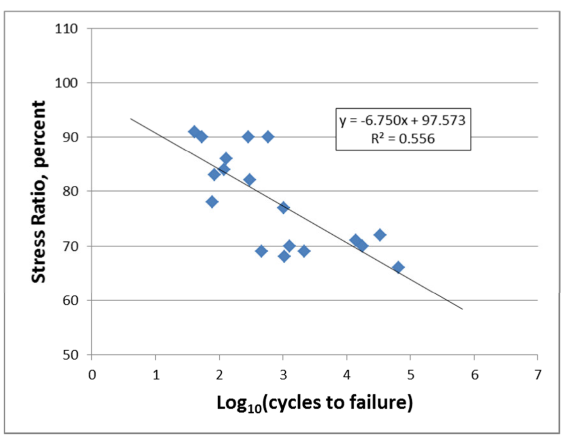

Figure 4. Fatigue Test Results for MRS2 Field-Cut Beams.

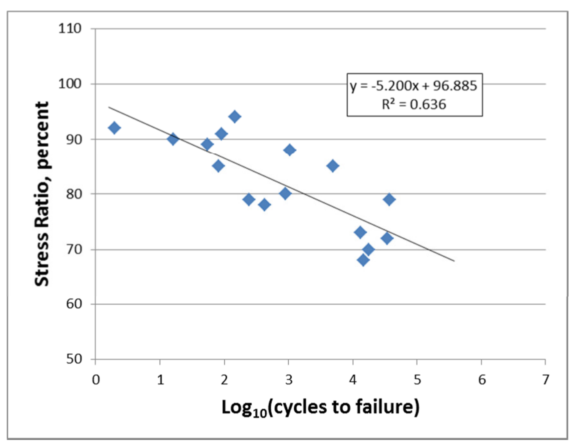

Figure 5. Fatigue Test Results for MRS3 Field-Cut Beams.

The plots in Figures 2 through 5 show a considerable amount of scatter, as is to be expected for fatigue test results, but the trends appear to be similar. A test was therefore made to estimate to what extent the combined test results can be represented by a common model. The procedure given in Pindyck and Rubinfeld [5], section 5.3.3, was followed. The procedure starts with the null hypothesis that the regressions for two sets of data are identical. Consider the regression equations for two sets of data (MRS1 and MRS2 field-cut beams, for example), which can be used to predict the expected stress ratio for a given number of cycles to failure:

$$y = A_1 + B_1 x$$
$$y = A_2 + B_2 x$$

Rewriting these equations to restore the stress ratio values for all samples by introducing the residuals:

$$Y_i = A_1 + B_1 X_i + \varepsilon_i$$
$$Y_j = A_2 + B_2 X_j + \varepsilon_j$$

Where

Y_i and Y_j are the stress ratios for the first and second sets of data, respectively;
X_i and X_j are the Log_{10}(cycles) for the first and second sets of data, respectively;
A_1 and A_2 are the intercepts for the first and second regressions, respectively;
B_1 and B_2 are the slopes for the first and second regressions, respectively; and
ε_i and ε_j are the residuals for the first and second sets of data, respectively.

After completing the regressions, the error sums of squares can be computed from the residuals with:

$$ESS_1 = \sum_{i=1}^{N} (Y_i - (A_1 + B_1 X_{1i}))^2$$
$$ESS_2 = \sum_{j=1}^{M} (Y_j - (A_2 + B_2 X_{2j}))^2$$

And the unrestricted error sum of squares for both sets of data combined is found by adding the individual sums:

$$ESS_{UR} = ESS_1 + ESS_2$$

If the null hypothesis is true, the two sets of data can be described by a single regression computed over all *N* plus *M* samples and the restricted error sum of squares computed with:

$$ESS_R = \sum_{k=1}^{N+M} (Y_k - (A_3 + B_3 X_{3k}))^2$$

Quoting from Pindyck and Rubinfeld [5]: "If the null hypothesis is true, the restrictions will not hurt the explanatory power of the model and ESS_R will not be much larger than ESS_{UR}. As before, we can perform an *F* test to see whether the difference between the two error sums of squares is significant. Since there are $N + M - 2K$ degrees of freedom in the unrestricted regression and there are *K* restrictions, the appropriate *F* statistic is"

$$F_{K,N+M-2K} = \frac{(ESS_R - ESS_{UR})/K}{ESS_{UR}/(N + M - 2K)}$$

"If the *F* statistic is larger than the critical value of the *F* distribution with *K* and *N* + *M* -2*K* degrees of freedom, we can reject the null hypothesis. Here rejection implies that the two separate regressions must be estimated: the data cannot be pooled."

An example of an *F* distribution copied from the open literature is shown in Figure 6. In this case, the critical value, X, is determined at the Alpha = 0.05 level and the area under the blackened area of the curve is 5 percent of the total area under the curve. If the critical value lies in the blackened area, the null hypothesis is rejected. An alternative reading of the criterion, adopted here, is to determine the level at which the hypothesis can be rejected.

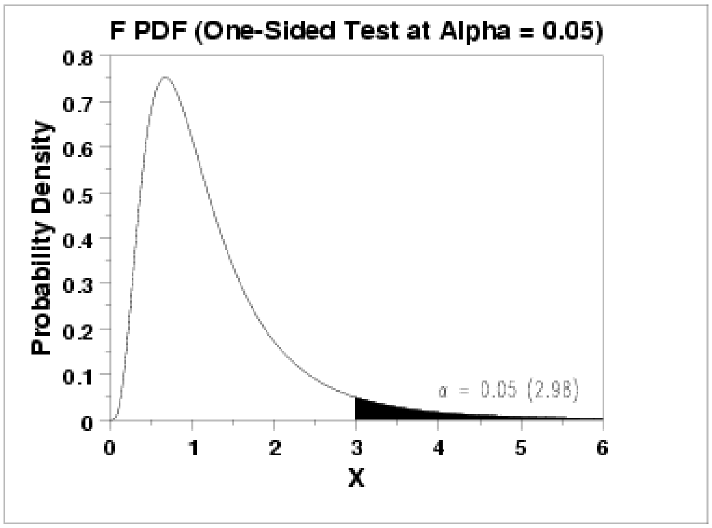

Figure 6. Example of the *F* Distribution Illustrating the Rejection Criterion at a Given Level of Confidence.

The procedure described above was implemented in an Excel spreadsheet. Taking pairs of the data sets, the F statistic for each pair was calculated with the equation given above, and the corresponding value of alpha found using the Excel function *F*.DIST(*F*, *K*, *N+M-2K*, TRUE). Table 3 shows the results.

Table 3.
Results of the *F*-Test Comparison of the Fatigue Beam Sample Data Sets.

Comparison	*K*	*N*	*M*	*N+M-2K*	*F(k, N+M-2K)*	*Alpha*
MRS1 Cut versus Cast	2	16	39	51	0.5892	0.5585
MRS1 Cut versus MRS2 Cut	2	16	18	30	3.7200	0.0360
MRS1 Cut versus MRS3 Cut	2	16	16	28	2.1223	0.1386
MRS2 Cut versus MRS3 Cut	2	18	16	30	2.1836	0.1302

The following can be concluded from the results of Table 3:

1. For MRS1, the fatigue results from the field-cut samples and the cast samples can both be represented by the same regression equation to a high level of confidence. This indicates that, when properly cured and stored, cast beam samples provide a very good estimate of the fatigue strength of in-place concrete.
2. For MRS1 vs. MRS2 field-cut samples, the null hypothesis can be rejected at alpha = 0.05 (or worse, 0.036) and a single regression equation should not be used.

3. For MRS1 vs. MRS3 field-cut samples, the null hypothesis can be rejected at alpha = 0.14 and a single regression equation can be used at a reasonably high level of confidence.
4. For MRS2 vs. MRS3 field-cut samples, the null hypothesis can be rejected at alpha = 0.13 and a single regression equation can be used at a reasonably high level of confidence.

SUMMARY OF CC-6 FINDINGS

Major findings from CC-6 full scale and laboratory tests suggest the following:

- Rigid pavement performance is strongly correlated to flexural strength, both from the full scale and laboratory tests. This indicates that the limitations on design strength contained in FAA Advisory Circulars 150/5320-6E [1] and consequently in FAA Advisory Circular 150/5370-10F [2] can be increased, provided cement contents are reasonable and not too high. From the CC-6 mixes a maximum cement content of less than about 700 lbs./cy. appears reasonable at this time.
- There were no major differences in the performance of rigid pavements on concrete and asphalt stabilized bases.
- Commonly referenced correlations to concrete elastic modulus from flexural strength should not be used for pavement design.
- The results from the laboratory fatigue tests do not provide any strong evidence that the fatigue strength of airport pavement concrete decreases with increase in flexural strength. In fact, the results suggest that the fatigue strength increases in direct proportion with flexural strength. In order to make more definitive statements on this question, more tests should be run with more samples per data set and for a wider range of mix designs. Fatigue testing is very time consuming and expensive and a comprehensive analysis of the existing data by an experienced statistician would be very beneficial in planning further testing.

DESIGN IMPLICATIONS

Trial pavement designs were performed for both light and heavy traffic on subgrades of different strengths. Subgrade strengths (modulus of subgrade reaction) of k = 100 psi/in. and 200 psi/in. were used with flexural strengths of 600 psi, 650 psi, 700 psi, and 750 psi for both the heavy and light traffic conditions summarized in Tables 4 and 5, respectively. To simplify the comparisons the modulus of both the asphalt and cement stabilized subbases was kept fixed at 400,000 psi and the thickness of each was kept constant at 6 inches. FAA's FAARFIELD computer program was used for the computations [1]. Since the cement stabilized subbase moduli are typically larger than this, one would expect a slightly greater decrease in slab thickness when cement stabilized subbase is used in lieu of asphalt stabilized subbase; however, this was not considered. The results of this sensitivity analysis are shown in Table 6.

Table 4.
Heavy Traffic Mix.

No.	Name	Gross Wt. lbs	Annual Departures	% Annual Growth
1	A380-800	1,239,000	148	0.00
2	A310-200	315,041	889	0.00
3	B737-800	174,700	1,066	0.00
4	B747-8 Freighter (Preliminary)	978,000	296	0.00
5	B777-300 Baseline	662,000	667	0.00
6	A340-500 std	813,947	1,111	0.00
7	A340-500 std Belly	813,947	1,111	0.00

Table 5.
Light Traffic Mix.

No.	Name	Gross Wt. lbs	Annual Departures	% Annual Growth
1	B757-200	250,000	100	0.00
2	A320-100	150,000	500	0.00
3	B737-500	134,000	1,200	0.00
4	Fokker F100	100,000	1,200	0.00

Table 6.
Variations in Slab Thickness with Flexural Strength.

Flex. Str. (psi)	*k* value (psi/in)	Traffic Condition	Slab h (in)
600	100	Heavy	20.5
		Light	15.8
	200	Heavy	18.3
		Light	14.0
650	100	Heavy	19.5
		Light	15.0
	200	Heavy	17.2
		Light	13.1
700	100	Heavy	18.7
		Light	14.2
	200	Heavy	16.1
		Light	12.4
750	100	Heavy	17.9
		Light	13.6
	200	Heavy	15.1
		Light	11.7

As shown in the Table 6, each 50 psi change in flexural strength translates to an average change in slab thickness of about 1-inch, or approximately 0.5-inch per 25 psi change in flexural strength.

COST IMPLICATIONS

The cost implications of implementing the major findings from CC-6 include decreases in costs associated with raising the flexural strength limitations and substituting cement stabilized for asphalt stabilized subbase. For the cost analyses, the following assumptions were made for the costs of concrete and cement and asphalt stabilized subbase after an internet search of recent bid tabulations for airport paving projects:

- P-501 concrete cost = $200 per cubic yard, or approximately $5.50 per sy per inch.
- P-403 asphalt base cost = $100 per ton, or approximately $34.50/sy for 6 inches.
- P-304 cement treated base cost = $100 per cy or approximately $16.50/sy for 6 inches.

Assuming an 18-inch slab for the heavy traffic mix and a 12-inch slab for the light traffic mix as representing typical airport pavement thicknesses, the relative costs of concrete paving would be $99 and $66 per square yard for the heavy and light traffic conditions, respectively. Assuming a 6-inch asphalt treated base would be constructed for each traffic condition, baseline pavement construction costs of $133.50/sy and $100.50/sy would result for the heavy and light traffic mixes, respectively. Now, for comparison purposes, assume the pavement design was performed with cement stabilized subbase in lieu of asphalt stabilize and pavement thicknesses were recomputed assuming an increase in flexural strength of 75 psi. That would make the slab thicknesses approximately 16.5-inches and 10.5-inches for the heavy and light traffic mixes, respectively, or an approximate 1.5-inch reduction in slab thickness for each. Concrete costs would then decrease by approximately $8.25/sy to $90.75/sy and $57.75/sy for heavy and light traffic conditions, respectively. These costs for the revised concrete thicknesses represent an approximate 8% and 12% decrease in concrete costs for the heavy and light pavements, respectively. If cement stabilized subbase is then substituted for asphalt stabilized subbase, a further reduction of $18/sy would be realized for a savings of over 50% in stabilize base costs. Total revised costs of approximately $107.75/sy and $74.25/sy for the heavy and light traffic conditions, respectively, would then result. When compared to the baseline conditions (i.e., lower flexural strength and asphalt stabilized subbase), percent reductions in pavement costs of approximately 19% and 26% result for heavy and light traffic conditions, respectively. The percent cost reductions would be higher for thinner slabs designed for commuter and general aviation airports.

Therefore, considering annual and geographic variations in costs, implementation of the research findings from CC-6 can result in an average relative decrease in rigid pavement costs of approximately 20%. And this does not consider sustainability issues and preservation of resources. Although it is recognized that pavement costs will vary, the cost assumptions provided herein should be reasonable for gaging the relative cost differences accruing from the implementation of CC-6 recommendations into FAA Advisory Circular 150/5320-6E.

SUGGESTIONS FOR FURTHER WORK

Although the CC-6 findings clearly support an increase in the flexural strength limitation for design, along with a cost preference for the use of cement stabilized subbase, further analysis is suggested in the following areas:

- Further laboratory fatigue testing should be performed to increase the population size for statistical analysis, but based on a comprehensive analysis of existing data by an experienced statistician.
- Assuming an across the board decrease in slab thicknesses, research to extend the rigid pavement design procedures to include top down, as well as bottom up, cracking should be initiated. In some instances, especially for rigid pavements designed for light traffic conditions at non-hub and regional airports, top down cracking may control the design in some instances, even though the bottom up cracking criteria is satisfied.
- Laboratory fatigue tests should be extended to estimate maximum cement contents whereby the risks of concrete embrittlement, shrinkage cracking and poor performance can be minimized.
- Incorporate the CC-6 findings into the research initiative for extending pavement life to 40 years at major hub airports. It is probable that in many instances, 40 year structural life rigid pavements are already being constructed when the actual flexural strengths exceed the design assumptions, which is often the case at major hub airports (e.g., JFK, IAD).

CONCLUSIONS

The CC-6 research findings can have significant cost and sustainability implications for rigid airport pavement construction by dispelling some of the conservatism in rigid pavement design procedures that were based on anecdotal information. Savings in pavement costs of approximately 20% are possible by implementing the findings from CC-6 into FAA design procedures [1]. Further, given the recent initiative to extend pavement life at major hub airports, the CC-6 findings should be incorporated into the 40-year life studies.

REFERENCES

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